Year: 2007

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Originally published at:
Thiel, Christian; Reiche, Johannes; Leiterer, Reik; Schmullius, Christiane (2007). Synergistic usage of ASAR WS and MERIS data for large scale water and vegetation monitoring in Africa - A science product of the AQUIFER project. In: Envisat Symposium 2007, Montreux (CH), 23 April 2007 - 27 April 2007. European Space Agency * Communication Production Office, online.

SYNERGISTIC USAGE OF ASAR WS AND MERIS DATA FOR LARGE SCALE WATER AND VEGETATION MONITORING IN AFRICA – A SCIENCE PRODUCT OF THE AQUIFER PROJECT

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ABSTRACT

Due to the specific climate conditions in the dry regions of Africa, an effective integrated water management is of great interest for the national authorities. This paper explains the workflow of the Aquifer Project product 'Water and Vegetation Monitoring over entire Aquifer'. The large scale water and vegetation monitoring will be accomplished for the transboundary aquifer Iullemeden, which represents one of the major freshwater reservoirs of Africa. By the synergetic use of radar and optical data land cover classification maps for four different times within one season are provided. The changes between these dates as well as the seasonal vegetation and water dynamics were analysed. Furthermore, by inclusion of specific contextual features of irrigated vegetation in the region, an irrigated vegetation map could be derived. The results demonstrate the high potential of Earth Observation data for the decision support for a more efficient water management in Africa.

1. INTRODUCTION

Water and vegetation monitoring over entire aquifers is necessary for an effective transboundary water management. This science product includes the detection of the land use and the water bodies at four different dates within one growing season as well as the changes between these dates. As remote sensing data two instruments from the ENVISAT satellite - MERIS and ASAR - are determined. Therefore, this science product shall demonstrate the performance and suitability of a synergetic usage of radar data and optical data for large scale water and vegetation monitoring.

1.1 Aquifer Project Background

The ESA financed Aquifer project is one of the TIGER individual demonstrator projects. It is embedded in the programmatic framework of the Data User Element (DUE), which aims to bring together the scientific research community working on pilot projects and the operational service suppliers providing Earth Observation (EO) products and sustainable services corresponding to the operational needs of the wider user community. The main objective of the Aquifer project is the support of the involved national authorities and international institutions with EO based technology to better manage internationally shared water resources and aquifers as well as to strengthen overall and integrated water management practices.

1.2 The Area of Interest SAI

The transboundary area of interest SAI (Systéme d'Aquifères d'Iullemeden) (Fig. 1) covers an area of 525.000 km², which includes parts of Niger, Nigeria, and Mali. It is located within 1°00'–10°00' E and 10°00'–19°00' N [1].

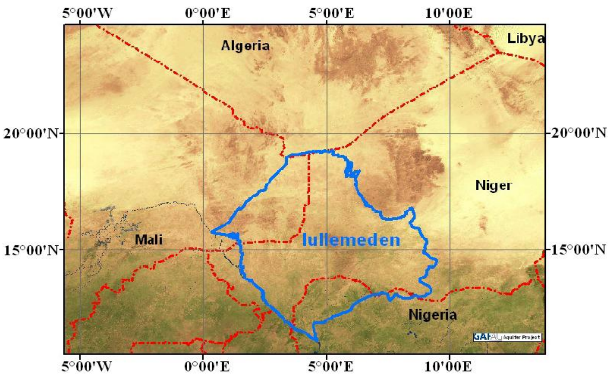

Figure 1. Area of interest SAI [1]

The climate in the SAI basin is characterised by yearly rain cycles. A short wet season with high precipitation from June to September is followed by a long dry season from October to mid-May. In the wet season the rain days and the annual rainfall decrease from the south to the north [2]. The floodplains of the main rivers are inundated during the wet season. The vegetation follows the yearly rain cycles with a temporal delay. During the long dry season the major part of the vegetation withers. It has no photosynthetic activity and appears as bald trees and bushes. Some water bodies dry up completely. The SAI multi-aquifer is affected by over extraction of water, human induced water pollution and salinisation [1].

In the SAI region two different main types of irrigated vegetation are present. The first type is intensive flood-recession agriculture in the floodplains of the main rivers (e.g. Sokoto) at the end of the wet season. The main crop plants are rice and sorghum (ADAMS 1993 in [3]). The second type enfolds agriculture areas which are irrigated from reservoirs (e.g. dams and lakes) over the whole year.

1.3 Data

The SAR data was acquired in Wide Swath Mode (VV) and delivered as level 1 product. This data product includes slant range to ground range corrections and covers a continuous area along the imaging swath. ASAR WSM scenes for the following acquisition dates have been used: April 2005, September 2005 and December 2005. The MERIS data was delivered as full resolution (FR) level 1b (L1b) data. MERIS FR L1b products provide geocoded Top-Of-the-Atmosphere (TOA) radiances [$Wsr^{-1}m^{-2}\mu m^{-1}$] with a pixel spacing of 260 m at nadir. A swath width of 1150 km allows the coverage of the entire earth surface within an interval of 3 days. The instrument measures the TOA radiance in 15 bands within the visible and near infrared range from 408 nm to 905 nm. MERIS FR scenes from the SAI region for the following dates have been used: May 2005, October 2005, December 2005 and March 2006.
As reference data a Landsat-7 mosaic from 2000 and NigeriaSat-1 scene from 2006 were available for a part of the AOI. Additionally, a high resolution open water surface mask (30m) for the whole SAI region was provided from the Aquifer project partner GAF.

2. PRE-PROCESSING OF EO-DATA

First of all, the EO-data were pre-processed on the base of commonly used techniques. For the data extraction, the radiometric calibration (including speckle filtering) and the reprojection of the SAR data, the GAMMA Remote Sensing Software was used. To reduce the speckle effect for an adequate estimate of σ^0, the *Frost* filter was applied. The performance of speckle reduction has been evaluated based on the *Filter Index*, the *Speckle Noise Index* and the *Equivalent Number of Looks*. To verify the texture and edge preservation, the *Edge Keeping Index* was used ([4]). Due to the limited availability of SAR scenes, the differences between the subswaths and the typical seasonal dependence of the vegetation cover, the application of a multi-temporal filtering has not been satisfactory. For the geocoding information, the SRTM 90 m elevation data of the *Consortium for Spatial Information (CGIAR-CSI)*, processed to fill data voids, was used. Due to the sensitivity of the backscattering coefficient to the terrain, the topographic normalisation process proposed by [5] was applied. For a full coverage of the area of interest the scenes were combined to create a consistent mosaic across the region. After the processing of the individual SAR scenes one problem persisted: It was impossible to completely adjust the backscatter intensity of the individual subswaths.

For the data extraction, the orthorectification and the reprojection of the MERIS data, the BEAM Software was used. To enable a comparison and to mosaic the different images, it was mandatory to convert the TOA radiance values into surface reflectance (SR). In order to correct for atmospheric influences, the *Simplified Method for Atmospheric Corrections (SMAC)* has been used [6]. The orthorectification was applied by using the GETASSE30 elevation data as a source for the required geocoded information. Additionally, the MERIS Level 2 biophysical vegetation variables (*fAPAR, fCover, LAI, LAI.Cab)* were generated by the MERIS TOA-VEG Processor [7]. The product layers have been co-located with the correspondent orthorectified MERIS image. Similar to the ASAR data, the scenes were combined to create a consistent mosaic across the region.

3. DATA ANALYSIS

The SAR data were well investigated in regard to their potential for land cover classification based on different commonly used methods.

The detection of water bodies using the ASAR data was limited by the low geometric resolution which anticipated the detection of the mostly narrow rivers. Furthermore C-Band is very sensitive for roughness on water surfaces due to windy conditions. Typically water bodies appear in SAR images as areas with a low backscattering, thus a simple threshold could be used for a successful extraction. Small waves on the water surface result in higher backscatter intensity [8] and hinder the distinction between water and the remaining areas (Fig. 2). Multitemporal analysis of all available ASAR mosaics as well as the additional use of texture features did not improve the distinction.

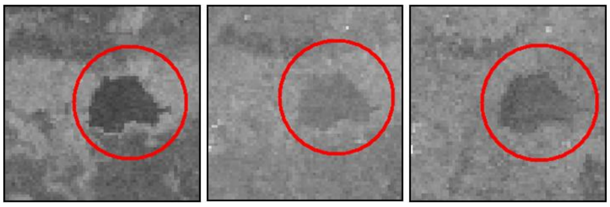

Figure 2. High backscatter from water bodies due to roughened surface (waves) at windy conditions (SAR data: May05 [left], Sep05 [mid], Dec05 [right])

The specific SAR technique offers a useful method for the detection of urban areas. The geometric characteristics of buildings causes dihedral scattering (double bounce), leading to very high backscatter and enables the classifications of urban areas using the ASAR backscatter information. A detection of urban areas with MERIS data in the SAI region is not feasible as the houses are primarily built of natural materials. This limits the separation between urban areas and the surrounding land cover by radiometric features.

The multitemporal mean image of the available ASAR mosaics (May05, Sep05, and Dec05) afforded the extraction of an urban mask (see Fig. 3) with an overall accuracy of 86%. The synergetic usage of the ASAR urban mask for a MERIS land cover classification shows the potential of the SAR data to overcome of the limitations of the optical data.

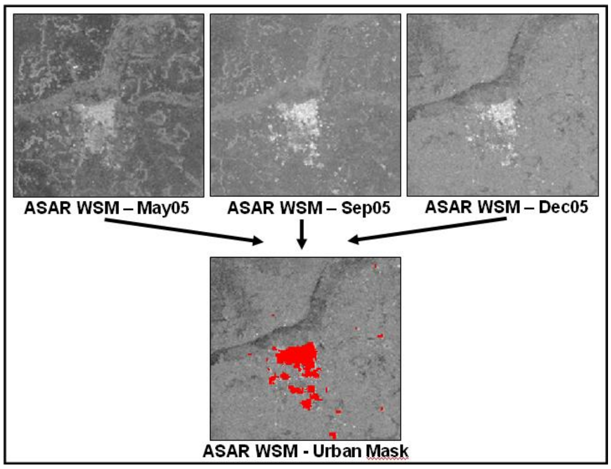

Figure 3. Extraction of the ASAR urban mask

Due to the discontinuities between the subswaths in the ASAR WS data (see Ch. 2) the distinction between vegetation types as well as irrigated and non-irrigated vegetation based on the ASAR data was anticipated.

Vegetation indices provide an excellent basis for the recording of vegetation dynamics and their phenology as well as for the distinction between vegetation and non-vegetation. Due to the inclusion of absorption characteristics of the vegetation, which are related to the seasonal and annual variations in the photosynthetic activity, vegetation indices are very suitable for the detection seasonal vegetation dynamics. For all MERIS mosaics the indices NDVI, SAVI (Soil Adjusted Vegetation Index) and the MTCI (MERIS Terrestrial Chlorophyll Index) were calculated (Eq. 1, 2).

$$SAVI = \frac{R_{Band13} - R_{Band7}}{R_{Band13} + R_{Band7} + L} \cdot (1 + L) \qquad (1)$$

$$MTCI = \frac{R_{Band10} - R_{Band9}}{R_{Band9} - R_{Band8}} \qquad (2)$$

The NDVI was calculated with the MERIS bands 13 (865 nm) and 7 (665 nm). Because of the low vegetation density in the SAI region, the value 1 was used as soil-brightness dependent correction factor L for the calculation of the SAVI. Compared to the NDVI, the SAVI stresses the vegetation areas more properly. The MTCI is sensitive to a wide range of chlorophyll contents and affords a good distinction between different photosynthetic activities [9].

Additionally to the introduced vegetation indices, the biophysical vegetation variables fAPAR and fCover were generated. The TOA-VEG Processor derives fAPAR and fCover directly from the MERIS L1b data (see Ch. 2). The fAPAR value is the fraction of the photosynthetically active radiation absorbed by the canopy, refers only to the green parts of the canopy (leaf chlorophyll content > 15µg.cm^{-2}) and varies from 0 (low) to 1 (high). fAPAR is comparable with the already existing MERIS Level 2 fAPAR product MERIS Global Vegetation Index (MGVI) [7]. fCover is the fraction of green vegetation covering a unit area of horizontal soil. It only considers green vegetation (leaf chlorophyll content > 15µg.cm^{-2}) and varies from 0 (bare soil) to 1 (full cover) [7].

One of the key tasks of the project is the distinction of irrigated and non-irrigated vegetation. A separability analysis was conducted to verify the option of a separation by the use of the 15 spectral MERIS bands. The separability analysis was accomplished for all four SAI mosaics and showed a poor separability of irrigated and non-irrigated vegetation at all four acquisition dates. This implies that both, the use of backscatter information of the ASAR date as well as the use of spectral information does not allow distinguishing between irrigated and non-irrigated vegetation in the SAI region.

4. CLASSIFICATION METHODS

The science product “Water and Vegetation Monitoring over entire Aquifer” includes the detection of the land cover and land use at four different acquisition dates as well as the changes between these dates and the investigation of the seasonal vegetation and water dynamics. For reaching these targets, three different groups of classification types were distinct and accomplished. The first group are the land cover and land cover change products. The second type is the *Irrigated Vegetation Map* product which has been derived by GIS analysis of the four land cover classifications and the additional high resolution water mask by inclusion of specific contextual features of irrigated vegetation in the SAI region. The pre-classification change products, focused on seasonal dynamics, provide the third product group.

4.1 Land cover classification and land cover change

For the land cover classification of the four acquisition dates, different classification approaches have been tested to map the Aquifer target classes: *water*, *irrigated vegetation, non-irrigated vegetation* and *other*.

Supervised (MLC), unsupervised (k-means clustering) and rule based (object oriented) classifications using the MERIS bands and the ASAR backscatter intensity as well as several indices (NDVI, MTCI, fAPAR, fCover) have been considered. Again the results confirmed that it is not possible to distinct irrigated and non-irrigated vegetation with the above mentioned input data. Consequently, for the land cover classification the land cover types *irrigated vegetation* and *non-irrigated vegetation* were combined to the land cover type *green vegetation*. The comparison and analysis of the several classifications results pointed out that the rule based (object oriented) approach is suited best for the land cover and land cover change classification.

During the progress of the classification hierarchy the basic classes *water*, *green vegetation* and *other* were subdivided into *water, clouds, urban, low green vegetation, high green vegetation, floodplain vegetation* and *other*. Urban areas were defined by means the extracted ASAR urban mask (see Ch. 3). For the cloud mask the high reflection of clouds and haze in the MERIS band 1 and the MERIS cloud ratio (band11 / band10) [10] have been used. Open water bodies (flowing & standing water) are characterised by very low reflection in the near infrared and particularly by very low values in the NDVI. The major limitation of the water body mask results from the low geometrical resolution of the MERIS data (260m). Thus, most of the rivers could not be detected. Hence, in the mapped pixel their spectral signature is mixed with the signature of the surrounding land cover.

Green vegetation was classified using the NDVI. *High green vegetation* and *low green vegetatio*n differ by a higher photosynthetic activity of the high green vegetation, which is indicated by high values of the MTCI and the fCover. The MERIS ratio (band14–band13) / (band14+band13) enabled to classify the inundated floodplains (Fig. 4), which are intensively cultivated by flood-recession agriculture (ADAMS 1993 in [3]). Thus, the detected floodplains in the SAI region can be classified as vegetation (*floodplain vegetation*). The radiometric properties of the floodplains are e mixture of the spectral characteristics of water and vegetation. The above-presented MERIS ratio emphasises inundate floodplains as well as water bodies (*Water (Floodplain)*). A higher NDVI differentiates the floodplain vegetation from water bodies.

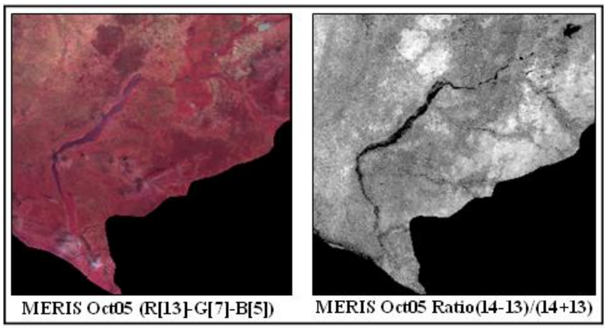

Figure 4. Use of the MERIS ratio (14-13) / (14+13) to differentiate inundate floodplains

During the dry season the main part of the vegetation in the SAI region has no photosynthetic activity and appears as bald and dry trees and bushes. Therefore it is to assume that the maximum extend of photosynthetic active vegetation (*green vegetation*) in the four individual maps represents the expansion of the non-photosynthetic vegetation for the whole season. By summating the green vegetation masks of all 4 acquisition dates, a mask for the extent of *non-photosynthetic vegetation* was generated.

The classification results of the four acquisition dates showed strong varieties in the photosynthetic activity of the vegetation (Fig. 5). This is based on the climate conditions in the SAI region (see Ch. 1).

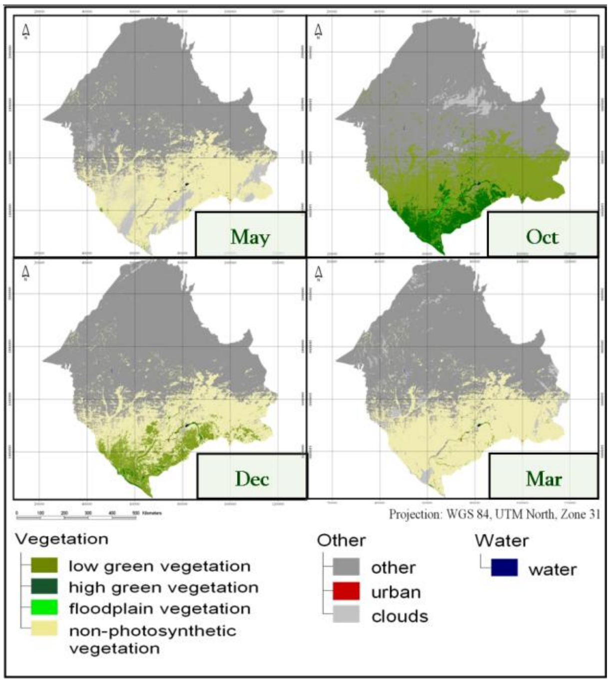

Figure 5. Land cover classification results for all acquisition dates

For the basic land cover classification products the subclasses were aggregated to the basic classes. The accuracy assessment has resulted the following overall accuracies (OA) and kappa indices (KI) for the basic land cover classification products: May05 [OA: 0.83 KI: 0.65], Oct05 [OA: 0.91; KI: 0.72], Dec05 [OA: 0.88; KI: 0.69], Mar06 [OA: 0.79; KI: 0.61].

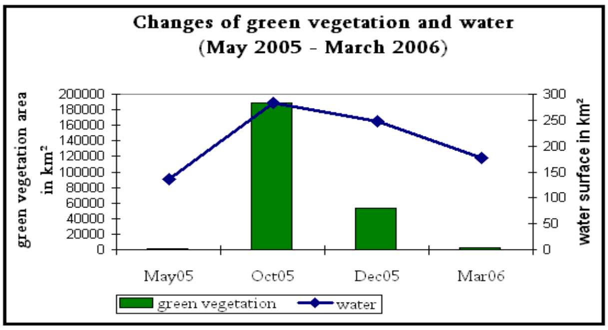

Figure 6. Vegetation and water changes in SAI

The area related analysis (Fig. 6) of the land cover classification products includes the area of green vegetation and water at the four acquisition dates. The changes between these dates point out the seasonal dynamics.

The post-classification land cover change products are based on the basic land cover classification products (all acquisition dates). For the generation of the vegetation change (phenology) map the four green vegetation masks were fused. The vegetation change map shows and distinguishes areas which feature green vegetation at one, two, three or four acquisition dates (Fig. 7).

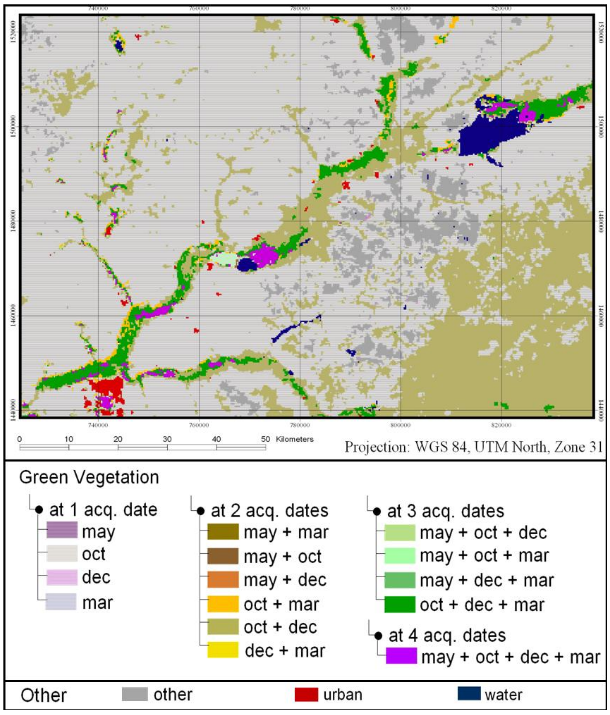

Figure 7. Vegetation land cover change map (subset of AOI)

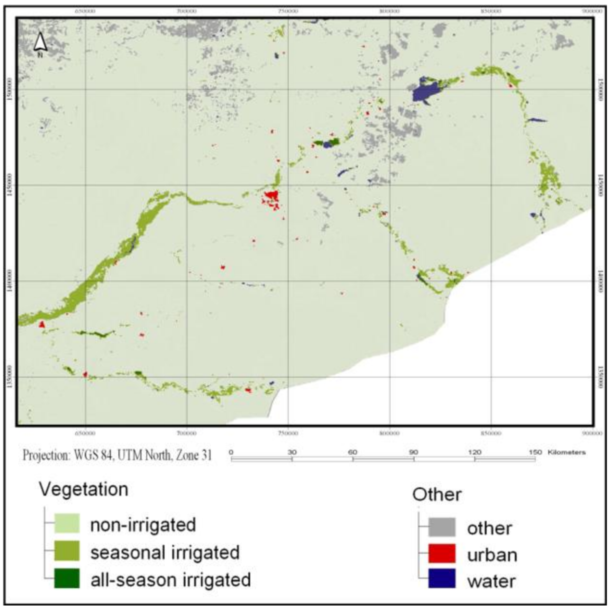

Figure 8. Irrigated vegetation map (subset of AOI)

4.2 Derivation of the Irrigated Vegetation Map

As stated above irrigated and non-irrigated vegetation cannot be separated by means of the on-hand ENVISAT data. However, with the inclusion of specific contextual information irrigated vegetation in the SAI region could be detected with sufficient accuracy. The two types of irrigated vegetation in the SAI region were already presented. The first type is the flood-recession agriculture. It is named *floodplain vegetation*. For the second type of irrigation water is taken from reservoirs and rivers. This type is characterised by a high photosynthetic activity during the irrigation period.

Generally irrigated vegetation is located close to open water bodies. The coarse geometric resolution of the MERIS water body mask anticipated its inclusion as contextual information layer - most rivers were not detected by means of MERIS data. The high resolution water mask, provided by an Aquifer project partner, offered the required information with sufficient accuracy. Thus, potential irrigation areas were defined by generating a 5 km buffer around all water bodies which was found the maximum distance to irrigated fields.

The generated water mask buffer and the extended land cover classification maps from the four acquisition dates were used in GIS analysis to derive irrigated vegetation areas. Areas were classified as irrigated vegetation if the following rules were true. First, the area has to be located inside the water mask buffer. Secondly, the area has to be classified as high green vegetation at least at two acquisition dates or it was classified as floodplain vegetation (flood-recession agriculture). Areas were defined as all-season irrigated vegetation if they were classified as high green vegetation at three or four acquisition dates. Accordingly such areas feature a high photosynthetic activity at least at one acquisition date during the late dry season (May 2005 or March 2006). Basically inside the SAI region just irrigated fields feature a very high vitality during the late dry season. The other regions were labelled as seasonal irrigated vegetation (Fig. 8).

4.3 Seasonal Vegetation Dynamic

The NDVI as well as the fAPAR follows the specific vegetation cycles dependent on the yearly rain cycles in the SAI region. Below the methodology for the production of the Seasonal Dynamic NDVI Map is presented. A similar methodology was applied for the production of the fAPAR map. To distinguish groups of vegetation by their seasonal (temporal) behaviour the k-means clustering algorithm was used. Beforehand, a common cloud mask for all four MERIS mosaics was generated. After cloud masking the NDVI mosaic layers were stacked to one multitemporal NDVI dataset. For the k-means clustering different numbers of initial classes were tested (4, 8, 10, 14). Ten initial classes are best suited to distinguish the multitemporal NDVI layerstack into groups of vegetation of different temporal behaviour. Fig. 9 depicts the temporal behaviour of the 10 NDVI clusters. Each cluster describes a vegetation group and its seasonal behaviour.

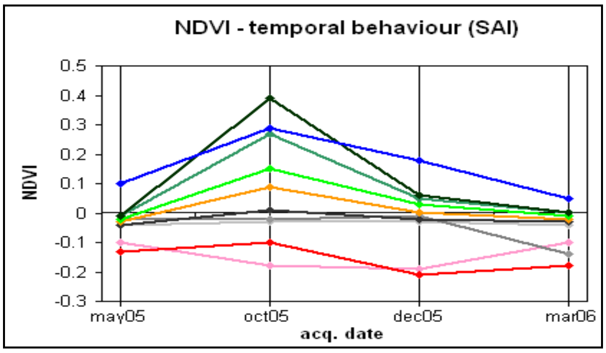

Figure 9. Temporal behaviour of NDVI in SAI

For labelling the different classes, thresholds were defined basing on visual interpretation of the image data and a statistical analysis of the clusters. Because of the strong radiometric effect of bare soil the threshold for photosynthetic activity was defined with an NDVI > 0. High photosynthetic activity was defined with an NDVI threshold > 0.15. Fig. 11 depicts a subset of the NDVI-seasonal change map.

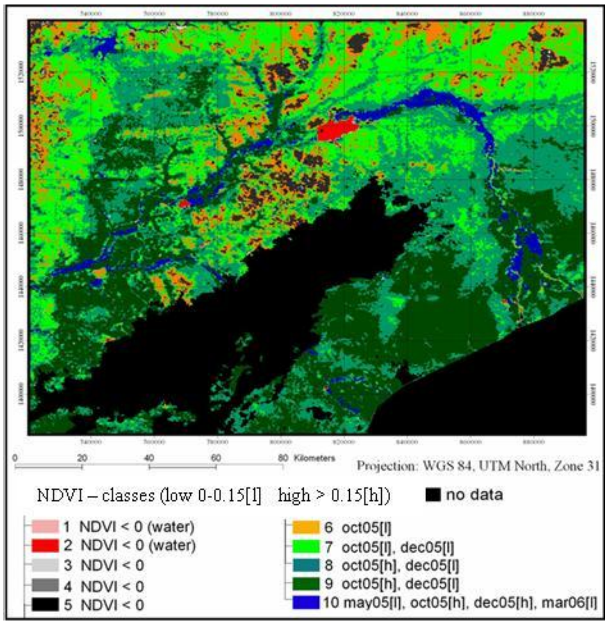

Figure 11. NDVI – Seasonal Change Map

5 CONCLUSIONS

Large scale water and vegetation monitoring using ASAR WS & MERIS data provides an appropriate opportunity for the decision support for an improved water management in Africa. The synergistic use of the SAR data improved the land cover classification by overcoming the optical limitations and demonstrated the high potential of thematic data fusion. The derivation of the irrigated vegetation areas was possible by including contextual information of irrigated vegetation in the region. This information provides a basis for the estimation of the water resources used for irrigation and enables a more efficient water management. In addition a methodology for the extraction of the vegetation's phenology was presented.

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